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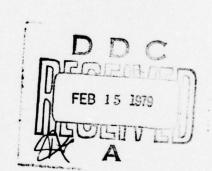DDC

Contract No. N00014-71-A-0124-002

LEVEL

Final Report

Design of Stiffened Shells.

by

Arnold Allentuch
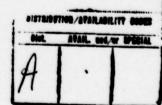
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The objectives of Contract No. N00014-67-A-0225-001, entitled Design of Stiffened Shells, followed by Contract No. N00014-71-A-0124-0002, have been (1) to take existing solutions to stiffened shell problems and develop fully documented digital computer programs, (2) to develop optimal designs of submersible structures and develop fully documented digital computer programs, and (3) to develop new solutions to stiffened shell problems where such solutions do not exist and develop fully documented computer programs. These analyses and digital computer programs have all been reported in detail in nine successive New Jersey Institute of Technology (formerly Newark College of Engineering) reports and in a succession of papers published in various professional journals.

What follows is a review of each of the nine publications resulting from this contractual effort. Reference is made to each of the original reports which describe in much greater detail the individual efforts contributing to total contractual objectives.

1. Digital Computer Program for Stresses in Eccentric Discontinuous Rings with Transition Section, by Arnold Allentuch* and Eugene Golub**, New Jersey Institute of Technology Report No. NV 1, Mechanical Engineering Department, August 1970.

*Dean of Research and Professor of Mechanical Engineering, New Jersey Institute of Technology.

**Professor of Civil and Environmental Engineering and Chairman of Department, New Jersey Institute of Technology.

Also published as

Design Program for Rings of Non-Uniform Thickness, by A. Allentuch and Eugene Golub, New Jersey Institute of Technology (formerly Newark College of Engineering) Computers and Structures, Vol. 1, pp. 131-155, Pergamon Press 1971.

This report presents a computer program which gives stresses in the rings and shell of hydrostatically loaded circumferentially stiffened shell. The ring stiffeners have two uniform but different sections with a smoothly varying transition section connecting the two uniform sections.

Several approximations to the exact interaction problem are given in reference [1]*. It was concluded that, within the limits of the parameter ranges chosen, these approximations were valid regardless of the length of each uniform section of the discontinuous frame. In the problem of reference [1] the bending stress was a first order effect, and, in fact, was found to depend most heavily on the constant term of the radial component of the Interaction load Fourier series. With this in mind the problem was solved by taking only this constant term into consideration. In effect, the interaction load was assumed to be constant and radial. This approximation to the exact problem, within the limit of the parameter ranges chosen, was found to be excellent. Further investigation indicated that the approximation described could be further simplified. This was accomplished by solving for the uniform interaction load between an infinitely long hydrostati-

*Numbers in brackets designate references at end of report.

cally loaded cylinder and a single uniform (based on a numerical average of the two cross sectional areas) reinforcing ring. This proved to be a reasonable approximation, within the limits of the chosen parameters, to the constant term of the interaction load. One, threfore, concludes that the interaction problem of the non-uniform frame with transition section, described earlier, and the hydrostatically loaded shell can be reduced to finding the stresses in a uniformly loaded ring composed of two uniform sections and connected by a smoothly varying transition section. The load (radial) on this ring is obtained from the solution of the inter-action problem of a single ring reinforcing an infinitely long hydrostatically loaded shell.

In this report emphasis is placed on the General Electric 605 Time Sharing Computer Program that was written for this ring analysis. A complete listing of the program and a typical run are presented.

2. Digital Computer Program for Asymptotic Solution for Short Ring-Reinforced Oval Cylinders by Arnold Allentuch and Eugene Golub, New Jersey Institute of Technology Report No. NV 2, Mechanical Engineering Department, August 1970.

Also published as

Design Program for Short Ring-Reinforced Oval Cylinder by E. Golub and A. Allentuch, New Jersey Institute of Technology, Computers and Structures, Vol. 1, pp. 435-464, Pergamon Press 1971.

The analysis of an oval shell, loaded hydrostatically, and periodically stiffened by uniform ring stiffeners was presented in Ref. [2]. In that paper, the authors, Vafakos, Nissel, and Kempner, used an energy approach to analyze the combined structure.

In carrying out the computations the authors encountered so many cases of differences of nearly equal numbers that they were forced to program in double precision in order to obtain useful output. The present analysis avoids the numerical difficulties and is substantially shorter.

An asymptotic expansion procedure is applied to the analysis of a typical bay in a hydrostatically loaded, ring-reinforced, non-circular cylinder. The existence of two distinct characteristic lengths is used in the construction of two asymptotic series which when combined, form the total solution.

In this report emphasis is placed on the General Electric 605 Time Sharing Computer Program that was written for this stiffened oval shell analysis. A complete listing of the program and a typical run are presented.

3. Digital Computer Program for Approximate Stress Concentration Analysis for Cylindrical Branch Pipe Connections by Eugene Golub and Arnold Allentuch, New Jersey Institute of Technology Report No. 3, Mechanical Engineering Department, August 1970.

Sections of this report are taken almost verbatim from Ref. [3].

The analysis of stresses in the vicinity of a branch pipe connection, acting as a stress raiser in a main pipe under internal pressure, is of considerable importance from both standpoints of economy and safety of piping systems. To provide a basis for a rational specification of rules for reinforcement of such connections, the Pressure Vessel Research Committee of the Welding Research Council has made a massive effort over more than a decade, involving over one hundred tests on steel and photoelastic models

and a large-scale digital computer analysis based on shell theory.

The enormous complexity of this stress analysis problem is reflected in the idealizations and limiting assumptions necessary to make a computer solution tractable. For example, the continuity of deformation over the interface of the juncture is relaxed in transition to shell theory to a continuity of the midsurface only; computer capacity and truncation errors further make it necessary to limit the continuity to only some 20 points around the circumference of the juncture. Moreover, the formulation leads into mathematical difficulties (slow convergence of series, and so on), and the range of validity is severely restricted as a result. Finally, there is little prospect of obtaining accurate stress values even from an "exact" solution by shell theory; the best that could be hoped for is to match the accuracy of the solution of the corresponding axisymmetric problem which early proved inadequate for stress analysis except with refinements, extrapolation, and empirical corrections. So, in spite of the impressive progress in numerical analysis and current development of very powerful finite element techniques, a rigorous solution is not a practical possibility as yet.

Instead, it is reasonable to explore which of the requirements of the problem are less essential and can be relaxed in order to produce an engineering solution. The success of this approach is witnessed for a wide range of still slender bodies in the various methods encompassed by the strength of materials discipline, in which bulk equilibrium is maintained, and bulk

deformation requirements are expressed by the Bernoulli-Kirchhoff assumption, while the requirements of equilibrium and continuity in the small are relaxed. A solution of this stress analysis problem, stresses in the vicinity of branch pipe connections to a pressurized cylindrical vessel, is presented by the "area method. A large number of test results confirm that this analysis is not only reasonably accurate, but is perhaps equal to or better than the most refined shell theory developed by the area method. It is not possible a priori to make any statements of the relative accuracy. In retrospect it may be conjectured that the complete bulk continuity of deformation across the critical section as realized by the area method presents a greater advantage than shell theory with its inherent, essentially correct and detailed account of the deformation of all parts of the shell except the critical region where the rate of curvature change is large.

This paper presents an area analysis of the problem of pressurized intersecting cylinders and compares the results with available test data. The analysis maintains the primary requirement of overall equilibrium, common in all rational analyses of mechanical strength. By a first approximation postulate of the deformation in vicinity of the juncture, an area method similar to that for spherical vessels is developed to predict the average maximum stress across the shell at the critical point. Finally, a simplified but reasonable hypothesis is made concerning the stress variation across the critical section, making it possible

to compute an approximate value of the maximum stress.

In this report emphasis is placed on the General Electric 605 Time Sharing Computer Program that was written for the "Tee" connection analysis. A complete listing of the program and a typical run are presented.

4. <u>Digital Computer Program for Approximate Stress-Concentration Analysis for a Nozzle in a Spherical Pressure Vessel</u> by Arnold Allentuch and Eugene Golub, New Jersey Institute of Technology, Report No. 4, Mechanical Engineering Department, September 1970.

Sections of this report are taken from Ref. [4].

The problem of determining the stress raising effect of an outlet placed in the wall of a pressure vessel has long been the subject of considerable engineering effort.

In addition to experiments, theoretical methods have been applied in the solution of such problems, notably shell theory. The present day shell theory is developed with reference to a mid-surface. However, for a large majority of practical problems, it is impossible to establish a mid-surface. Thus, for the typical cross section there is no system of shell coordinates that locate each point in a unique way at the intersection of the nozzle and spherical pressure vessel.

Following the principle of St. Venant, the stresses in
the neighborhood of the intersection are indeterminate by shell
theory. In addition to difficulties in the practical solution
of shell problems, this is the reason that shell theory apparently
cannot be used to predict the stesses at such junctures with
normally accepted engineering accuracy.

It is therefore reasonable to consider other lines of
approach, and develop a different basis of assumptions to ob-
tain a theory in which the difficulties outlined above do not
arise. One way is to resort to three-dimensional theory of
elasticity, but an alternative is the regression to simple con-
cepts, such as static equilibrium, continuity of stresses, etc.
It is not to be expected that this would yield results of an
accuracy comparable to that of a more refined theory.

Based on the area method of Lind [4], this report pre-
sents a computer program for a simple semi-empirical analysis
suitable for practical design. The method usually yields results
equal or superior in accuracy to shell theory, and it is ap-
plicable to reinforced configurations that are difficult to treat
by any other method.

The second part of this report and of New Jersey Institute of Technology Reports NV 5-10 deal with the optimal design of submersible structures*.

Activities in this area were devoted to three interrelated tasks.

1. Application of optimization methods to problems of interest to submarine hull designers so as to study the difficulties and benefits that may result from such application.

2. Generation of new or modified optimization and analysis techniques needed to more effectively treat such problems.

3. Development of specific optimal design tools for use by U. S. Naval submarine designers.

The initial effort applied a new optimization method that had earlier proved effective in treating aerospace type shell structures [5] to the problem of least weight static design of submarine pressure hulls. NAVSEC was consulted on the formulation of the problem so that within constraints on security, the problem reflected their current procedures for the design of such structures. It was found that the hull design problem was much more difficult than the earlier aerospace problem. The optimization method used could not obtain reliable solutions where all hull dimensions that were considered variable were independent and continuous. A new procedure was therefore developed wherein the original problem was cast as a mixed

*Investigations dealing with this section of the contractual obligations were conducted by Arnold Allentuch, Dean of Research and Professor of Mechanical Engineering, New Jersey Institute of Technology and Michael Pappas, Associate Professor of Mechanical Engineering, New Jersey Institute of Technology.

continuous discrete formulation with the frame spacing considered
as a discrete quantity (a more realistic formulation since the
number of frames are integers) and with the frame web variables
coupled. A new single variable discrete search was combined
with the original continuous optimization procedure to solve
the problem.

The results of this research was reported in N.J.I.T. report
NV-5 which was subsequently published as ref. [6]. This report
presents the optimization methodology problem treated and a
computer program, complete with user instructions, for an auto-
mated optimal design capability. This procedure was then applied
to a parametric study of such hulls in order to investigate their
optimal properties. The most interesting result of this study
was that for a wide range of frame spacings, the least-weight
design is relatively insensitive to frame spacing. Thus, additional
design considerations such as cost, vibrational characteristics,
etc., can, if properly introduced, greatly improve the design
without a significant weight penalty.

The result of this effort was reported in NJIT report NV-6
which was subsequently published as ref. [7]. This report, in
addition to the parametric study, presents an improved and more
flexible version of the automated design capability given in
NJIT report NV-5.

A limitation of the above procedures is that the material
thickness dimensions are treated as continuous variables. Such
a limitation is allowable for naval submarine design since any
desired thickness may be ordered. It is, however, desirable,

particularly from a cost standpoint, to use a standard avail-
able thickness or to confine thickness to discrete values. An
analysis of available techniques for treating multivariable
mixed problems indicated that none were likely to be sufficiently
reliable to treat the problem at hand.

A new method was then developed for mixed problems. This
procedure is given in NJIT report NV-7 which was subsequently
published as ref. [8] and applied to the hull design problem. The
results of this application along with parametric studies and a
computer program with user instructions is given in NJIT report
NV-8 which was later published as ref. [9].

Another limitation of the above procedures is that the
equation for predicting general instability assumes that the
minimum buckling pressure collapse mode has a single longitudinal
half-wave (m=1). This assumption is conventionally made by
submarine hull designers. The results of the studies associated
with the above research suggested, however, that even using a
factor of safety of 2 for general instability, the nature of the
optimal designs at design depths often used in such structures
are such that this assumption might not be valid particularly
if high strength steels are used.

The optimization procedures developed earlier were thus
combined with an analysis procedure that admits more than one
longitudinal half-wave. A new program was developed and used
to study the optimal characteristics of hulls designed without
using the m=1 assumption. The study confirmed the concern that
the minimum buckling mode can, for loading parameters and

materials properties in the range of interest to naval submarine hull designers be greater than 1 for optimal hull configurations. This study was reported in NJIT report NV-9 which was subsequently published as ref. [10].

It is of interest to note that personel at NAVSEC are familiar with this study and now check their designs to see if the minimum buckling mode has n > 1.

The problem of the lack of optimization algorithm reliability encountered in research is not unique to the method used. Eason and Fenton(11) in a comparison study of some 21 algorithms found none solved all the problems they investigated. The typical procedure solved less than half and some solved none. The algorithm of ref [5],in.fact, is a relatively reliable procedure. It solved all but one of the test problems of Eason and Fenton and came within 10% of the solution on the one it failed to solve [12].

It was felt that an improved algorithm was therefore of general importance. Furthermore, one difficulty of the pressure hull design problem appeared to make the development of a superior optimization algorithm of particular importance if new problems associated with such structures were to be explored.

The development of such a procedure was therefore undertaken. The task was completed after termination of the contract and thus no report was issued on this work. The results of this effort was however published in ref [13]. The new procedure was found to be generally superior to all those

studied by Eason and Fenton. It solved all test problems.
This work naturally aroused substantial interest.

The shell optimization work received considerable atten-
tion. Shell optimization program decks were requested and
used by List 1:

I. Maison
Southwest Research Institute

K. Chary
Chicago Bridge and Iron Co.

J. F. Saunders
Perry Submarine Co.

C. F. Miller
General Dynamics
Electric Boat Division

J. W. Sharer
Applied Research Laboratory

P. Vachjetpan
University College
Cardiff, Wales

Requests for reports and papers on the shell optimization
projects were made by List 2:

S. Garian
Newport News Drydock & Ship Bldg Co.

Librarian
Charles Stark Draper Laboratory

G. J. Simites
Georgia Institute of Technology

D. Bushnell
Lockheed Palo Alto Research Sub.

L. P. Felton
Univ. of California, Los Angeles

L. Lukas
Nod Palmatonkov
Czechoslovakia

Y. Bengash
Thames Polytechnic
England

S. Ramamurthy
Cornell Univ.

S. N. Patnaik
Universte De Moncton
Canada

Akbar & Aleen
Consulting Engineers
Pakistan

S. K. Aggarwae
University of Rookee
India

K. Subbaraj
India Institute of Tech
Madras, India

J. Sharma
University of Rookee
India

T. Kant
Indian Institute of Tech
Bombay, India

M. Aviel
Technion-Israel Institute of Tech
Israel

J. Sobrenczanski
NASA Langley

J. A. Starnes Jr.
NASA, Langley

In addition to the general optimization literature also seemed of substantial interest. Copies of program decks for general nonlinear programming algorithms developed or refined under the contract were requested and used by List 3:

E. Eason
Saudia Subs

D. M. Himmelblau
University of Texas at Austin

M. L. Crow
Dresser Industries Inc.

M. P. Kamat
Virginia Polytechnic Institute

C. Giiven
Marmara Scientific & Research Council
Turkey

P. Wang
John Deere Product Engrg. Center

S. J. Rice
Materials Science Corp.

K. Ragsdell
Purdue University

Request for papers and reports on this topic were made

by List 4:

C. Misclke
Iowa State Univ.

B. L. Pierson
Iowa State Univ.

B. Sureskwara
Underwater Laboratories Inc.

D. J. Jones
High Speed Dynamics Sub.
Canada

R. G. Brush
General Dynamics
Convair Division

Y. S. Lai
Chicago Vrudge & Iron Co.

T. Kant
Indian Institute of Tech
Bombay, India

J. J. Jankins
University of Va.

T. J. Higgins
University of Wisc., Madison

S. Schoenfelt
Techische Hocksule-Karl-Marx-Stadt
DDR

B. Bharathi-Devi
National Aeronautical Lab.
Bungalore, India

P. C. Kapui
Indian Institute of Technology
Kampur, India

R. D. Bonnell
University of South Carolina

R. T. Haftka
Technion-Israel Institute of Technology

A. Koren
Israel Desalination Engineering
Israel

P. L. Dhar
India Institute of Technology
New Delhi, India

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5. Pappas, M., and Amba-Rao, C. L., "A Direct Search Algorithm for Automated Optimum Structural Design", AIAA Journal, Vol 9, No. 3, March, 1971, pp. 387-393.

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8. Pappas, M., and Allentuch, A., "Mathematical Programming Procedures for Mixed Discrete-Continuous Design Problems" Journal of Engrg for Industry, Trans, ASME, Series B, Vol. 96, No. 1, pp. 105-112, Feb, 1974.

9. Pappas, M., and Allentuch, A., "Extended Capability for Automated Design of Frame-Stiffened, Submersible, Cylindrical Shells", Computers and Structures Vol. 4, pp. 1025-1057, 1974.

10. Pappas, M., and Allentuch, A., "Pressure Hull Optimization Using General Instability Equations Admitting more than one Longtudinal Buckling Half-Wave", Journal of Ship Research Vol. 19 No. pp. 18-22, 1975.

11. Eason, E. D., and Fenton, R. G., "A Comparison of Numerical Optimization Methods for Engineering Design", Journal of Engineering for Industry, Trans ASME, Series B, Vol. 96, No. 1, pp. 196-201, Feb 1974.

12. Pappas, M., "Performance of the Direct Search Design Algorithm as a Numerical Optimization Procedure", AIAA Journal, Vol. 13, No. 6, pp. 827-829, 1975.

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